Flash Flood Guidance Improvement Team

"Flash Flood", 1951 to 1976, Walter Burt Adams, with permission by Joseph Levy, Jr.

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1. Executive Summary

The Flash Flood Guidance Improvement Team (FFGIT) began work in July 2002 with the mission to determine what steps could be taken in a one to two year time frame to improve the state of Flash Flood Guidance (FFG) issued by RFCs in support of the NWS hydrologic services program. The recommendations will be presented to the Operations Subcommittee of the NWS Corporate Board.

The team examined the current state of the science, implementation, and support of the generation of FFG. It used input from the RFC Operations Team report, feedback from NWS field offices, and proposals made at the Development and Operations Hydrologist Science Conference (June, 2002) in an effort to identify potential approaches for improvement.

It was recognized no single approach for the production of FFG can address all needs of the flash flood program across the country in light of the short time horizon of the team's focus. Therefore, the team makes the following recommendations based on its research and investigations. More detail is provided in the Recommendations section of this report.

1. The existing approach to generating FFG is viewed to be at the end of its life span. However, steps can and should be taken to improve the current state and implementation of the Flash Flood Guidance System (FFGS). (Details: Section 7)

2. The existing FFG generation method does not address areas of the country where land characteristics and rainfall intensity influence the occurrence of flash flooding more than soil moisture. A project currently under development in the Western Region should be pursued to provide better flash flood services to these areas of the country. (Details: Section 6)

3. Distributed modeling will be the long term scientific enhancement for flash flood modeling. In the short term, a Statistical Distributed method, proposed by OHD, should be pursued. This method helps to lay the foundation for general distributed hydrologic modeling. (Details: Section 5)

4. There currently is no method to measure the performance of the FFG product. To identify service improvement areas, a national FFG verification program should be developed. It is recommended a follow-on team pursue this issue. (Details: Section 8)

5. NWS and Regions must take an active role in the coordination, implementation, and support of these recommendations. National and regional oversight is needed to coordinate these efforts which include (but are not limited to) areas of service definition, policy, support, improvement, training, and enhancement. (Details: Section 10)

2. Introduction

Over the last 30 years, flooding and flash flooding have caused more deaths than any other weather-related phenomenon (U.S. National Hazard Statistics, National Weather Service) . The National Weather Service (NWS), in support of its mission to protect life and property, provides the watch and warning service to the nation for flash flooding. This service is provided through the efforts of River Forecast Centers (RFCs), who provide an assessment of the hydrologic state of watersheds in the form of Flash Flood Guidance (FFG) to the Weather Forecast Offices (WFOs), and the WFOs, who monitor for the conditions that could initiate flash flooding and issue watches and warnings when conditions warrant them. All components contributing to this service - the data, the technology, the training, the support, and future enhancements - must be coordinated and optimized to maximize the level of service the NWS provides.

Concerns have developed over time on a number of aspects regarding FFG, many of which have been voiced in the RFC Operations Survey Team report, specifically in Finding 4, "Flash Flood Guidance is currently a weak link in the flash flood program." As a result of the level of concern on that issue, Gary Carter, Chief, Office of Hydrologic Development (OHD) requested the formation of a team, under the direction of the RFC Development Manager, to focus on realistic recommendations for improving flash flood guidance in a one to two year time-frame. The Flash Flood Guidance Improvement Team (FFGIT) was formed in the summer of 2002 to focus on improving the FFG product and service provided by the RFCs in support of the WFOs' watch/warning decision making process. The team charter is provided in Appendix A. This report summarizes the findings and recommendations of the team.

3. Background

Some definitions to keep in mind while reading along in this report (Sweeney, 1992):

- Flash Flood - A flood which occurs within six hours of the causative event. In some parts of the Nation, the actual time threshold for an event to be considered a flash flood may be less than 6 hours.

- Flash Flood Guidance - The general term which refers to the average rain needed over an area during a specified period of time to initiate flooding on small streams in an area.

- Threshold Runoff - Runoff (in depth) from a rain of a specified duration that causes a small stream to slightly exceed bankfull.

- Unit Hydrograph - method to convert runoff volume into instantaneous discharge at a point. It is based on a given unit of runoff from a storm of specified duration - for example, one inch of runoff for a 1 hour storm.

A flash flood program was implemented within the NWS in response to a recommendation in the disaster survey report on the July 4-5, 1969 floods in the Akron, OH area. Flash flood guidance thereafter was produced at RFCs, using different methods at each RFC but providing FFG for the warning areas of the supported weather offices, typically either counties or zones, for periods from one to twenty-four hours.

During the 1970s and 1980s, the NWS River Forecast System (NWSRFS) was developed principally by the Office of Hydrology's Hydrologic Research Lab (now the Hydrology Lab (HL) in OHD) and implemented at all RFCs during the 1980s. The NWSRFS provided a uniform, supportable software platform from which the RFCs could produce their river forecast guidance products. The generation of FFG, however, still was performed using local, RFC-developed software.

In the late 1980s, an effort was undertaken by the HRL to provide a consistent method for the generation of FFG, integrated with NWSRFS, to address many of the concerns regarding FFG that existed at that time. The result was the Flash Flood Guidance System (FFGS) (Sweeney, 1992) that has been implemented at the majority of RFCs (see Attachment B for current status). FFGS provides the ability to produce hydrologic information for HRAP (Hydrologic Rainfall Analysis Project) cells (4km x 4km cells on polar stereographic projection) to match up with the precipitation estimates provided via the Precipitation Processing Subsystem (PPS) of the NEXRAD radars deployed across the country. The FFGS provides the ability to utilize hydrologic information resulting from routine RFC operational modeling (on a forecast basin basis) into the FFG generation, to assign threshold runoff values at each HRAP grid location, and to produce FFG values for each HRAP grid cell within an RFC's area of responsibility. Once information is produced at each grid point, grid values can be accumulated and averaged over any defined area (typically counties) to meet the requirements of the service program.

At the same time development of the FFG production tools was underway, new tools to utilize the information in support of the WFO's watch/warning decision making program were being created. During the 1980s and 1990s, a package known as Areal Mean Basin Estimated Rainfall algorithm (AMBER; Davis and Jendrowski, 1996) was developed at the Pittsburgh WFO to pinpoint locations where flash flooding is likely. Using the increased spatial and temporal resolution of improving radar systems (initially RADAP-II, then NEXRAD) and the emergence of GIS tools (such as ArcView), AMBER allowed WFO forecasters to identify small basins experiencing high rainfall intensity. A system known as FFMP (Flash Flood Monitoring and Prediction) was developed for implementation in AWIPS as a WFO operational tool, resulting as an outgrowth and merging of existing capabilities within the WFO Hydrologic Forecast System (WHFS) HydroView application and the System for Convection Analysis and Nowcasting (SCAN), as well as AMBER. The FFMP provides continuous monitoring of rainfall rate and its comparison to FFG for high resolution stream basins. It can provide NWS forecasters with automated alerts when a dangerous flood situation may be developing on a given stream or catchment.

At this time, FFGS is the primary tool at RFCs for the generation of FFG and FFMP is the principal tool at WFOs for identifying areas of flash flood concern. Both of these packages are deployed on AWIPS. The "handoff point", where information produced by the RFCs is picked up by the WFOs, is the gridded FFG. The information flow for the generation and use of FFG is shown in Figure 1. The current status of FFG production is shown in Appendix B.

4. Methodology

To form recommendations in response to the Team charter, the team first needed to identify problem areas regarding FFG, then focus on those issues where improvements could be achieved in the one to two year time frame.

The problem identification process started at the OHD Science Conference held in June 2002. Many shortcomings related to FFG were discussed and proposals on how to make improvements were presented. An initial list of issues for the team to investigate was generated out of the discussions conducted and proposals made at that conference. In addition, the team reviewed the draft report of the RFC Operations Survey team for further guidance. The team then conducted a survey of all the NWS offices via each regional HSD asking for any work underway at a local office, or at the regional level, that could be considered in fulfilling the Team's mission.

The investigations led the team to form four subgroups to investigate the first four topics listed below. In addition, the team identified two other major issues for consideration (5-6 below).

1. Limitations of the existing FFG science in flash flood modeling,

2. Limitations of the existing FFGS in determining FFG,

3. Limitations of the existing FFGS in its implementation,

4. Lack of a verification system for FFG,

5. Misunderstandings on the generation and use of FFG,

6. Need of a better defined support structure at the national level for FFG production and use.

The issues and potential solutions are addressed in the following sections.

5. Limitations of existing FFG science in flash flood modeling

5.1. Issues

Methods used in the current NWS Flash-Flood Guidance (FFG) system were originally developed decades ago before the existence of radar data, high-speed computer networks, and Geographic Information Systems (GIS). These methods are simple by today's computational standards, and given the complexity of the hydrologic processes being modeled and the limited available input data, these tools need to be revamped to move the program forward. Some advances have been made in automating FFG techniques (Sweeney, 1992) and upgrading model components (e.g. use of the Sacramento and other continuous simulation models to replace the older event-based models); however, significant changes are needed so flash-flood hydrology procedures can take full advantage of data collected by the NEXRAD systems.

Three basic problems with the science in the current FFG system are:

1. Current lumped modeling basis for FFG,
2. Uncertainty in threshold runoff values,
3. Misapplication of threshold runoff concept.

5.1.1. Lumped modeling basis

Rainfall-runoff models used to derive 1 hr, 3 hr, and 6 hr rainfall-runoff curves for the FFG system were calibrated for large basins, typically using a 6 hour time step. Modeling at this spatial resolution will average out the FFG for a large basin. In a case when heavy rainfall occurs in only part of a basin, the spatially averaged FFG value for that basin will be too high for areas receiving heavy rainfall and too low for areas that did not receive heavy rain (assuming spatially uniform threshold runoff values for the basin, a reasonable assumption).

It is understood that lumped hydrologic model simulations (e.g. Sacramento model) are sensitive to the spatial and temporal scales at which the model parameters are calibrated (Finnerty *et al.*, 1997; Koren *et al.*, 1999). Therefore, rainfall-runoff parameters derived at the basin scale (~300 – 5000 km^2 for NWS applications) with a 6-hour time step are probably not applicable at the scales of interest for flash-flood applications (< 6 hr, < 300 km^2), although they may provide reasonable results under certain conditions.

The ramifications of using RFC scale rainfall-runoff models for flash-flood applications tend to be more acute in arid and urban settings. In these settings, flash-floods are thought to be more dependent on rainfall intensity than antecedent soil moisture. Infiltration excess type models attempting to deal explicitly with rainfall intensity are particularly sensitive to changes in spatial and temporal scales (Koren *et al.*, 1999). Therefore, it will be particularly important in these areas to apply hydrologic models at the same spatial and temporal scales for which they were developed.

5.1.2. Uncertainty in threshold runoff values

Threshold runoff (TRO) is defined as the ratio of a basin's unit hydrograph peak (Q_p) to its flood flow (Q_p); TRO = Q_p/Q_f. The existing FFGS methodology requires TRO values to derive FFG. To provide information on the small scale appropriate for flash flood forecasting, TRO values are needed on a small basin scale and must be derived efficiently. Several NWS attempts have been made to derive TRO objectively, but this work has shown significant uncertainty in TRO values, both in estimating the local flow rate that will cause flash flooding (Q_f) and the unit hydrograph peaks (Q_p).

There are few easily accessible data sets available to validate flooding flow and unit hydrograph estimates on small basins and to quantify uncertainties in TRO estimates. A recent effort at RFCs to use the two-year peak flood values estimated from USGS regression equations as a surrogate for flooding flow yielded some undesirable spatial inconsistencies in TRO values within USGS regions and across state borders and USGS regions. The overall significance of errors in TRO estimates relative to rainfall-runoff errors in producing FFG estimates is unknown, and the relative significance of these two types of errors likely varies for different parts of the country.

Theoretical TRO calculations from the work of Reed et al. (2002) and the earlier work by Carpenter et al. (1999) show threshold runoff can have significant local variations due to differences in basin and stream morphology. As an example, 1-hour TRO values for small (FFMP-scale) subbasins in the Blue River basin in Oklahoma are shown in Figures 2a and 2b. For basins ranging in size from 2 mi^2 to 100 mi^2, the range of 1-hr TRO values is from 13 mm to 29 mm (a range of about ½ inch). Uncertainty analysis shows that the 16% and 84% uncertainty bounds for values in this basin can span about a 1-inch range. Given that about 68% of current operational 1 hr TRO values in 10 RFCs across the country are between 0 in. and ½ in. and 21% of the values are between ½ in. and 1 in., the computed estimates of local variability and uncertainty seem significant.

5.1.3. Misapplication of threshold runoff concept

In FFGS, TRO values are treated as areal properties when really they are point properties describing characteristics of points on a channel network.

The move from county-based values to values based on small basins mapped to 4-km HRAP grid cells was supposed to address this problem. However, the current gridded approach lacks information about cell-to-cell connectivity and therefore cannot differentiate between local and cumulative TRO values. Using either small subbasin connectivity or grid cell-to-cell connectivity, which is fundamental to distributed modeling, will solve this problem.

The relatively coarse 4-km cell resolution may have limitations for some flash flood situations. The morphology of small basins like those delineated for FFMP cannot be explicitly considered with a 4-km gridded model. Figure 2c shows 4-km gridded TRO values interpolated from the small subbasin values can reasonably reflect the overall TRO pattern in the basin, but that local smoothing still can be significant. Point 1 is within a subbasin having a threshold runoff value of 30 mm and a cell with a value of 22.5 mm. The differences are due strictly to interpolation required within the current system.

5.2. Potential Solutions for Improving Science

In order to make real improvements to scientific methods used within FFG, it may be more efficient to implement a new system than to attempt modifications of the existing system. Use of a distributed model is a way to address some of the scale issues with the current FFG system. The HL recently has developed practical and useful distributed modeling software called the HL-Research Modeling System (HL-RMS). Although there still are many unknowns, a framework in which distributed models can be used to assist with flash-flood forecasting could provide immediate benefits and address major concerns with the existing FFG system.

At the 2002 NWS Hydrology Science Conference held in Silver Spring, MD, John Schaake proposed a methodology now termed statistical-distributed modeling. The idea is to use distributed modeling to account for the uncertainty in our ability to predict flash flooding. The physical processes causing flash floods and river floods are not much different; however, predictive uncertainties tend to be greater for flash floods than for river floods. This is partly due to errors in rainfall data which tend to average out over the larger spatial and temporal scales associated with river floods. In addition, predictive models for river floods can be calibrated using streamflow observations at forecast points. Most streams where flash flood predictions are required do not have streamflow gages.

The basic idea of the statistical-distributed modeling approach is to use retrospective distributed model runs as a measure of flood severity for ungaged locations. To implement this, a distributed model would be run using historical archives of gridded multi-sensor precipitation estimates (MPE), then results would be analyzed to establish flood frequency information for each model element (e.g. grid cells or small subbasins). For any model element, simulation results obtained by running the same distributed model in real-time can be compared to the flood-frequency information derived for that element. For model elements where actual flood damage levels are known and observed streamflow data are available, flood frequency information can be used to indicate which modeled flood frequencies should be of concern in a given area. Both flood frequency statistics and real-time simulations are produced using the same model so the comparison is useful even when modeled flows are not a perfect match for reality. Because of this, the method can be implemented initially using a-priori rainfall-runoff parameters and can potentially provide benefits without requiring extensive model calibration.

Science and technology currently used in the HL-RMS can be used to implement the statistical-distributed modeling approach. Implementation details for this approach still need to be identified, but major steps to be considered in developing a prototype system are outlined below.

5.2.1. HL-RMS

For several years, researchers in the HL have investigated distributed hydrologic modeling techniques resulting in the development of the HL-RMS. This suite of programs has already proven useful in simulation mode, producing simulations which match or exceed the performance of calibrated lumped models for RFC scale basins, and providing some reasonable simulations at interior points. Results using HL-RMS have been presented at several conferences and HL-RMS is one of the models studied in the Distributed Modeling Intercomparison Project (DMIP). A conference paper describing HL-RMS is currently available (http://hsp.nws.noaa.gov/oh/hrl/presentations/fihm02/pdfs/rms_lv.pdf), and a journal article is currently being prepared for submission to the *Journal of Hydrology*.

Parameter estimation procedures are a key feature of HL-RMS described in these papers. Gridded a-priori estimates of SAC-SMA parameters (Koren et al., 2000; Koren et al., 2001) are available and could be used initially without calibration in the statistical-distributed modeling framework. Distributed routing parameter estimates can be derived using Digital Elevation Model (DEM) data, flow measurement data at selected gages, and laws of geomorphology. Systematic analysis of flow measurement data at many stations is needed to implement this approach over large areas. Some tools have been developed to simplify this type of analysis.

5.2.2. Current Plans with HL-RMS Relevant to Flash Floods

There are a number of ongoing and planned HL-RMS applications and enhancements. All studies with HL-RMS will add to our knowledge of modeling hydrologic processes at different scales and to indicate the viability of using radar-based precipitation data for modeling in different parts of the country. It now is appropriate to begin step-by-step, quasi real-time testing of distributed modeling components that might provide immediate operational benefits. Taking initial implementation steps will begin a useful cycle of testing and evaluation.

Two planned activities are described here because they are the most immediately relevant to the flash flood problem.

a. Run the existing grid-based rainfall-runoff component of HL-RMS with a-priori SAC-SMA parameters in real-time over a large area (e.g. an RFC or multiple RFCs). Include snow and frozen ground components as soon as possible. The resulting grids of soil moisture, depth of frozen ground, etc. will be useful products for operations and research for RFCs, the National Centers for Environmental Prediction (NCEP), and the academic community. As they become available, real-time soil moisture grids will provide information which is useful for flash flood threat assessment.

b. Analyze flow measurement data at many stations over large areas to refine parameter estimation methods, provide better guidance for model users in deriving local parameters, and to develop basic routing parameter grids for large areas. These routing parameter estimates are critical for applications of the distributed model at any basin scale. A short-term use of these parameter grids at RFCs would be to use HL-RMS to route runoff from existing lumped models; thereby, capturing spatial variability in the rainfall but not requiring re-calibration. This routing parameter estimation is also a prerequisite for implementing the statistical-distributed modeling approach.

5.2.3. Spatial Resolution

The generation of small subbasins (down to ~5 km^2) for FFMP type applications has generated a lot of interest in small scale hydrology. HL-RMS currently uses 16 km^2 HRAP cells. Even at the 16 km^2 grid scale there are considerable uncertainties in the ability to estimate rainfall, and the uncertainties for smaller subbasins are likely to be greater. Currently, there is a lack of knowledge to determine the tradeoffs between increased uncertainty and increased spatial specificity when moving to smaller modeling elements. More studies to consider the most appropriate model element size and temporal scales for flash flood modeling are recommended. In the interim, it is perfectly reasonable to develop a system which uses 4-km grid cells for runoff and routing calculations, a substantial increase in resolution over the existing FFG system (300-5000 km^2).

It also may be beneficial to modify HL-RMS so it can deal with subbasin modeling elements. The required modifications to HL-RMS would be significant but not overwhelming. This would help in the understanding of both the computational efficiency and accuracy tradeoffs of subbasins versus 4-km grid cells. For the Ft. Smith, AR, radar, there are 14,276 FFMP subbasin polygons with an average size of 11 km^2; therefore, a subbasin model would require about 1.5 times as many elements as a 16 km^2 grid model covering the same area. Tests indicate a real time model running on 14,276 elements is computationally feasible. The gridded version of HL-RMS applied to the entire Arkansas River basin using 24,447 model elements showed modest computational requirements (~5 minutes for a 10 day simulation at 1 hour time steps).

One advantage of the subbasin approach is its ability to capture the geomorphologic character of the small subbasins (See Figure 2). In order to do this with a gridded approach, much smaller grid cells are required.

5.2.4. Temporal Resolution

A simple implementation of the proposed approach using 4-km grid cells and an hourly time step should be an improvement over the existing lumped FFG approach. As with the 4-km spatial resolution, a potential temporal modeling limitation is that an hourly time step may not be adequate for modeling flash floods in very small basins. The computational algorithms currently used in HL-RMS are easily adaptable to finer spatial and temporal scales; however, differences in the availability and quality of precipitation estimates at these finer scales will certainly affect the reliability of the statistical-distributed modeling approach. For example, the high resolution (5-6 minute, 1 degree by 1-km) radar-only precipitation estimates currently used by FFMP will contain more errors and uncertainty than products from the multi-sensor precipitation estimator (MPE) (hourly, 4-km). The only way to quantify and understand the differences in how models driven by these two types of input data will perform is to develop and test a prototype system.

One challenge in using radar-based precipitation archives for simulation studies is that these archives may be non-stationary. Studies of multi-sensor precipitation grids from ABRFC have revealed systematic biases over time due to a number of factors (Johnson et al., 1999; Young et al., 2000; Wang, et al., 2000). Re-analysis of radar and gage data would be required to produce a continuous unbiased archive. Although reanalysis studies may require considerable effort, the results would benefit many projects including distributed modeling research for RFC scale and flash flood scale applications, MPE research and development, use of radar-based products for hydrological design studies, and Model Output Statistics (MOS) work.

5.2.5. Gains and Shortcomings

The statistical-distributed modeling approach addresses major scientific concerns with the current system, and provides a more consistent framework for eliminating implementation problems. Although a dramatic change from current Flash-Flood Guidance procedures, this is a change necessary to really improve flash-flood hydrology procedures.

The theory of the statistical-distributed modeling approach is sound. In fact, some aspects of the proposed approach are simply extensions of accepted hydrologic methods. Use of flood-frequencies to define flood levels has been part of available threshold runoff procedures for several years; however, the distributed modeling approach to flood-frequency analysis differs in several important ways from use of USGS regression equations: (1) distributed model flood-frequencies will have a direct relationship to real-time simulation results, (2) once a system is set up, modeled flood-frequencies can be easily updated as more precipitation data become available, and (3) results should be more spatially consistent than previous results using USGS regression equations. The HL-RMS approach uses kinematic routing and estimates routing parameters using geomorphologic relationships based on similar theories used to develop the geomorphologic unit hydrograph (GUH) (Rodriguez-Iturbe et al., 1982a; Rodriguez-Iturbe et al., 1982b). Carpenter et al. (1999) use the GUH for threshold runoff calculations. A major practical difference in favor of implementing the statistical-distributed modeling approach is that hydraulic data to support HL-RMS parameter estimation procedures are collected at every rated USGS streamflow gage in the country, while hydraulic data required to support the GUH approach as implemented by Carpenter et al. (1999) are less widely available.

Initial implementations of the statistical-distributed modeling approach will be limited to non-snow areas with gridded precipitation archives of a reasonable length. The required archive length is not known, but archives with 5 – 10 years of data seem like a reasonable starting point because bankfull flows typically have relatively short return periods (~ 2 - 5 years). As gridded archives continue to accrue, results can only improve. A snow/frozen ground component is a planned addition to HL-RMS as research and development continues, but initial testing will be in areas with limited snow impact.

5.2.6. Costs and Time Frame

Scientific development and testing of a statistical-distributed modeling prototype is a reasonable goal for a two year planning horizon; however, wide spread field implementation of this approach is beyond the two-year planning horizon mandated for the FFGIT team. Because so many factors come into play, a realistic estimate of the time required for wide spread field implementation is beyond the scope of this report. Results of prototype testing will certainly be invaluable in guiding future field implementation.

5.2.7. Summary

In developing a statistical-distributed modeling system, the criteria for success is to make scientific and operational improvements to flash flood modeling over the current FFG system. With this in mind:

- The outlook for this approach is positive.
- Not all of the pertinent scientific questions need to be answered before benefits can be gleaned from this development. A simple system should be developed first and then refined.
- Development and testing of a simple prototype can reasonably be accomplished in 2 years.
- Testing a simple prototype can answer both key science questions and provide insights into computational resource requirements.
- A more realistic time frame for field implementation can be estimated after prototype testing.
- Because the approach significantly overlaps with other existing and planned projects, early communication and collaboration among NWS personnel on different project teams is recommended.
- Where successfully deployed, the proposed system could replace the current FFG system.

A key need for development and evaluation of the proposed statistical-distributed modeling approach is flow data for small streams. As discussed in Section 8.2 (Development of FFG Verification), similar data are needed for verifying the current FFG system, and some useful small stream data sets may already be available.

6. Limitations of the existing FFGS in determining FFG

6.1. Issues

There are areas of the country where flash flooding is intensity driven and is influenced more by terrain, land cover, soil type, geology and land use characteristics than soil moisture. For example, in the mountain west, flash floods frequently occur in canyon areas of very small drainage basins and are the product of isolated storms. In short distances, land characteristics change significantly from areas where flash flooding is unlikely to where there always is a threat for flash flooding regardless of the recent rainfall history (Figures 3 and 4). And, in those situations flash floods may not need to reach a "criteria" such as bankfull to put the group at greatest risk in harm's way (namely hikers and back country enthusiasts), as illustrated in Figure 5.

Currently, radar technology is utilized as one of the main sources of flash flood information in the west. FFMP inputs radar-based precipitation estimates (for one degree by one kilometer bins) and maps those bins to small river basins (Figure 6). Those basins are then color coded to indicate precipitation estimates and flash flood potential. The great unknown with this process is the basin characteristics of those color coded basins. Different rainfall intensities will cause varying amounts of flash flooding depending on basin characteristics. FFMP maps precipitation data to basins whose hydrologic characteristics are unknown to the forecaster. Are the basins impermeable? Are the basins void of vegetation, or are they hosting lush forests? Are the basins steep sloped, or flat pans? Have wildfires altered basin hydrologic characteristics? The answers to these questions are crucial in the thought process to issue a flash flood warning. Currently, there is not an NWS-wide method to determine these underlying factors. Even though the current FFGS can assign individual grid cells with a "fixed" guidance value (canyon and urban areas typically respond to the same amount of rain over various intervals regardless of antecedent conditions), there are no objective methods to identify those areas where assigning fixed values is appropriate and to determine the appropriate fixed value. As a result of the listed limitations, in many areas, gridded FFG values are not issued (Figure 7).

6.2. Potential Solutions - A New Approach to Determining FFG

The Colorado Basin River Forecast Center (CBRFC) is leading the CBRFC/Western Region Flash Flood Analysis Project to identify areas where flash flooding occurs, regardless of antecedent moisture conditions, areas such as rock canyons and urban environments. It is a GIS-based method to produce more useful and accurate flash flood potential (FFP) and guidance (FFG) products. Two important factors in this project are the use of observed flash flood event information and the emphasis in using rainfall intensity combined with terrain characteristics. These factors drive flash flooding more than soil moisture in much of the West and in other parts of the country. Application of this approach will initially be limited to headwaters only as there is no hydrologic routing capability built into the design.

Initially the project focus is on defining an area's (basin's) relative potential for flash flooding. This will be accomplished by investigating the questions:

- What physiographic properties of an area correlate with a rapid hydrologic response to heavy rainfall and thus make it susceptible to flash flooding?
- Can we identify these areas with available datasets?

A variety of GIS raster data layers providing information about terrain features, vegetation, forest cover, soil characteristics, land use, etc. will be analyzed in an attempt to answer these questions. These layers will independently be re-classified into discrete levels corresponding to increased risk of flash flooding. The newly classified layers will be weighted and combined resulting in a static layer of FFP indicators describing an area's relative potential for flash flooding. This will be compared and verified with actual flash flood observation data, where available, as well as with local knowledge. This raster layer of FFP will then be interpolated to FFMP type (FFMP or AMBER) basins and field tested at two Weather Forecast Offices in the CBRFC's area of responsibility. A sample map image of basin FFP is presented in Figure 8.

The project is at the point where field testing is about to begin at the Salt Lake and Flagstaff WFO's with a preliminary FFP layer. A fire perimeter and burn severity layer has been incorporated into the analysis for the Flagstaff FFP coverage from the recent Rodeo-Chedeski fire. The first results of the application of this procedure are expected in late summer 2003.

Future enhancements focus on dynamic adjustment of the static FFP grid. Work is currently being done to include a short time scale soil moisture component based on output from the Multi-Precipitation Estimator (MPE). There also are plans to adjust the FFP grid for seasonal variation (e.g. vegetation state, snowcover), and event variation (e.g. wildfire burn area).

Another enhancement under consideration is the incorporation of urbanization data into the analysis to create the static FFP grid. This would help to identify and isolate areas where land development has altered the runoff characteristics of small basins.

Ideas are currently being postulated on how to derive actual FFG values upon successful creation of an FFP grid. Possibilities include a simple approach of assigning FFG values to each of the FFP classifications, applying spatial regression techniques to data from observed flash flood events, using information on the return frequency precipitation associated with flash flood events, and others to be determined.

All work will be coordinated with other NWS development offices to ensure system and development plans compatibility.

7. Limitations of the existing FFGS in its implementation

7.1. Issues

There are numerous implementation problems with the current FFG system. Some are due to FFGS configuration settings or definitions, whereas others are due to FFGS or supporting program shortcomings. Also, the derivation of TRO on a small-basin scale, a key component to producing gridded FFG, has not progressed as rapidly as needed. The major deficiencies are listed and described below.

7.1.1. Information gaps inside a single RFC's area of responsibility

The gridded FFG often contains missing information inside a single RFC's area of responsibility and along the shared borders between neighboring RFCs (Figure 7). For each grid cell, two inputs are required to produce an FFG value; (1) a threshold runoff value and, (2) a rainfall runoff curve. When either one or both of these inputs are missing, gridded FFG cannot be computed for that grid cell.

Grid cells without an assigned threshold runoff value defined have been observed inside an RFC area of responsibility and along the border of an adjoining RFC (Figure 9). Since there is no threshold runoff defined for these grid cells, they do not produce a flash flood guidance value, creating a gap in the grid field.

Observations and investigation have shown there are cases where rainfall runoff curves are not assigned to various grid cells, one of the necessary inputs to produce a flash flood guidance value. When a basin is initialized in PPINIT (operational parameter initialization program in NWSRFS) using the @DEFINE BASIN command, grid cells falling within the basin's boundary should be assigned to that basin. Investigation has shown that some grid cells do **not** get assigned to the basin. This is most apparent along the boundaries between adjoining basins. Other cells not assigned to a basin are evident but there is no apparent pattern to explain this occurrence (Figure 10). As a result, these grid cells cannot compute a flash flood guidance value.

7.1.2. Overlapping values along the shared border between neighboring RFCs

The gridded FFG may contain overlapping values along the shared border between neighboring RFCs. The user controls within the FFGS program have an option to account for gaps of missing information outlined above in finding 7.1.1. The Grid Fill Control can be used to populate missing flash flood guidance grids with the values from neighboring grid cells. When this control is applied, the FFG grid tends to "bleed" or "spill" across the RFC boundary into another RFC area of responsibility. These grids, near the RFC borders, often get assigned two different values. When this occurs, FFMP has to decide which grid cell value to use and may choose the wrong one.

By default, the Grid Fill Control is set to 3 in FFGS, causing empty grid cells to be filled 3 columns and rows to the left/right and above/below, respectively. The result typically shows up as overlapping grids at RFC boundaries.

7.1.3. Inconsistent gridded FFG across adjacent RFC boundaries

FFG values sometimes change abruptly at RFC boundaries (Figure 7). These changes must be determined to be hydrologically correct and based on sound reasoning. Where that is not the case, these inconsistencies must be resolved between the RFCs when there is no sound reasoning to explain them.

Some possible causes for inconsistency:

1. Different rainfall/runoff models.
   Continuous versus event-based models; different continuous models.
2. Different parameters in the rainfall/runoff models.
   Inconsistencies in the model parameter values for the same models used by different RFCs in adjacent basins. A brief study was conducted on this issue to see which model components were most influential in FFG generation, but no conclusions were drawn.
3. Different parameters in the SNOW-17 model (where used).
   In the northern latitudes, where the SNOW-17 model is used, FFG can be affected by the SNOW-17 model parameters much like it is by the soil moisture accounting models. Also, FFG can be set to "ignore" the SNOW-17 model altogether, causing significant changes in values where the snow pack water content is considerable and "ripe" or nearly so. If one RFC is ignoring the snow model and the other is using the snow model, differences in values are likely.
4. Same rainfall/runoff models, but managed differently.
   The RFC forecaster has several approaches available to modify the river model to make the modeled flow match the real-time flow of the river. These different management philosophies can be exposed when unexplainable differences in FFG values are produced, for example, modifying the soil conditions rather than a flow condition, that is, using an RRICHNG vs UHCHNG mod.
5. Differences in threshold runoff values.
   Threshold runoff values may differ from one RFC to another at their shared border. Significant differences in values need to be justified with some physical or hydrologic evidence.
6. Differences in parameter settings and options being used in FFGS.
   There exist several options, or user controls, in FFGS to control how FFG values are produced. Two examples of these controls are: setting maximum and minimum FFG values, and assigning the percent of bankfull flow considered to be flooding. It may not be clear how some of these controls are to be used and therefore, they are used incorrectly, not at all, and they are not coordinated among the RFCs.
7. Use of rainfall input from different sources in adjacent RFCs.

RFCs can use different rainfall estimates with different bias characteristics, primarily mean areal precipitation estimates based on WSR-88D and gages (MAPX) vs. estimates based on gages alone (MAP).

7.1.4. Lack of tools to manually edit FFG product before dissemination

Once the gridded FFG fields have been produced by FFGS, there is no tool available for the forecaster to apply any adjustments or manual edits to the grids before dissemination. A nationally supported graphical editing tool would be beneficial for coordination with a neighboring RFC and to fix gross errors that may arise from the output grids of FFGS.

In the current system, if the forecaster desires a change to the FFG grids, he/she must go back to the hydrologic models, make modifications, and then rerun FFGS to produce new FFG grids. This process can be time consuming and the forecaster is not always certain the model changes will produce the desired output in the FFG grids. Having a graphical editing tool would allow the RFC forecaster to quickly apply changes for coordination purposes, allowing time to review the root cause for the inconsistencies and make necessary simulation model adjustments.

7.1.5. Problems in Gridded TRO Derivation

A key part of the existing system is the assignment of threshold runoff values (TRO) to each 4 km HRAP cell. The derivation of gridded TRO has proven to be a problem despite at least two efforts in creating objective derivation methods (see section 5.1.2). The most recent attempt at deriving gridded TRO, using two year peak flow values from USGS regression equations, yielded undesirable results. One of the problems with this approach is that regression equations available originally derived independently for different states, causing discontinuities along political boundaries. In addition, some RFCs felt that direct use of the two year peak flow regression equations led to TRO estimates that were too high. Because of uncertainties and discontinuities in applying the regression equation approach, the method has not produced results discernibly better than existing county values in many parts of the country. Therefore, an increased gridded resolution has not been attained in many areas.

7.2. Potential Solutions

7.2.1. Information gaps inside a single RFC's area of responsibility

Investigation of this issue revealed three potential causes for the missing information:

1. Assignment of each HRAP grid cell to the proper RFC,
2. Eliminating information gaps inside and along an RFC boundary
3. Proper grid cell assignment within NWSRFS OFS.

Potential solutions of each issue are discussed below.

7.2.1.1. Assignment of each HRAP grid cell to the proper RFC

A precise and complete assignment of HRAP grid cells to the appropriate RFC at RFC borders must be performed. This can be done using GIS software to analyze and to assign grid points to the appropriate RFC. Doing so ensures completeness of gridded FFG information at RFC borders. This also ensures that FFG values provided for each individual HRAP grid cell come only from one RFC. At this time, there are no known efforts underway to review and coordinate HRAP grid cell assignment. This effort requires analysis tools, most likely GIS-based tools, to be developed. Once the tools are available it is estimated approximately one week would be needed to perform the analysis and to coordinate any grid cell reassignments. Since this affects all RFCs, this effort should be spearheaded at the national level, most likely as a fallout of the solutions listed in Section 10 for coordinating national support for FFG production and use.

7.2.1.2. Eliminating information gaps inside and along an RFC boundary

Within each RFC boundary, threshold runoff (TRO) values must be assigned to each HRAP grid cell to provide proper input data for FFGS to produce a complete gridded FFG field. A method needs to be devised to efficiently interrogate, edit and redefine the TRO grids. One RFC utilized a GIS package to perform this task with success. The original map is shown in Figure 11 and the corrected map is shown in Figure 12.

There are three possible approaches to ensure TRO values are assigned at all grid points. The first involves using the existing FFGS system to fill in missing values manually. Instructions can be found in the NWSRFS users manual in Section VI.3.6A SETUP-GRID. This is a manual procedure where only one grid box can be filled in at a time, so it can be tedious and time consuming. Another approach is to generate the TRO grids with the avThreshR program which is part of the AWIPS hydrology software which will generate a grid with no missing values. The third option is to convert the current FFGS TRO values from xmrg (the native format) to ascii - then import them into ArcView with Spatial Analyst, fill in the missing values, then export from ArcView as ascii. The FFG software will import ascii grids of TRO to be used in computations. An effort to develop the analysis tools and for analyses to be performed and corrections to be applied at each RFC is estimated to take two to four months. This same mechanism can be used at the RFC borders once HRAP grid cell assignment has been made,

7.2.1.3. Proper grid cell assignment in NWSRFS OFS

This problem has been reported to the RFC Support Team and AWIPS, resulting in an AWIPS Discrepancy Report. The HL has investigated and found two problems: (1) instances where entire HRAP line segments (rows) have been omitted and (2) instances where individual grid bins or parts of line segments are missing. HL has provided a solution for problem 1 for the PPINIT program as part of NWSRFS Release 22, scheduled to be delivered by AWIPS in the OB-1 release. This solution requires RFCs to redefine their basins to fill in the missing grid cells. Problem 2 has not been solved and requires additional work by HL.

7.2.2. Overlapping values along the shared border between neighboring RFCs.

Once the corrective actions of Section 7.2.1.1 are complete (proper HRAP grid cell assignment) then the FFGS Grid Fill Control can be set to zero. This control no longer would be needed to overcome imprecision. This would eliminate confusion at the WFO as to which RFC's FFG value is used within FFMP. This approach has been tested and shown to produce the desired results. This can be accomplished by RFC personnel and only takes a few minutes to apply.

7.2.3. Providing consistency in gridded FFG values across adjacent RFC boundaries

The RFCs need to take a more active approach to coordinate and remove the inconsistencies that can not be validated by sound hydrologic reasoning. Greater RFC coordination regarding this issue is necessary. MBRFC and ABRFC have already held meetings to resolve differences in threshold runoff and rainfall/runoff model parameters where applicable. More consistent gridded FFG values have been observed at the shared MBRFC and ABRFC border (see Figure 7). There are travel and time considerations to this approach as face-to-face meetings have shown to be most effective between the MBRFC and ABRFC. It is estimated this effort could be accomplished in a two to three month time frame if aggressively pursued.

7.2.4. Providing the ability to edit the gridded FFG values at the RFCs

A graphical editing tool should be made available to RFC forecasters to edit and adjust gridded FFG values when deemed appropriate. A possibility is the use of GFE, which would provide the added benefit of being the same tool used for other RFC gridded field manipulation (such as QPF). The ability to underlay previous field issuance is required. At this time the NWRFC is testing the use of GFE for manipulating QPF and temperature grids. Those efforts, if proven successful, could be followed up with testing on manipulating FFG grids. An initial time estimate for completing this task is approximately one year, but a better estimate could be made upon completion of current testing at NWRFC.

7.2.5. An alternative method for deriving gridded TRO

Given the problems with the TRO derivations using the USGS regression equations, one RFC is using its own methodology for TRO derivation. The method requires gaged small basins with reliable USGS rating curves and easily estimated bankfull stages (determined by site visits, which, when applied to the rating, yield the bankfull flow). Unit hydrographs are derived from event analyses and the TRO for that small basin is derived accordingly (see section 5.1.2). The basin TRO value then is assigned to each HRAP grid cell within that basin. This is repeated for as many basins as possible to provide a representative sample. These values then are contoured in a geologically consistent manner.

This method is viable where the above conditions are met, but the site visits would require involvement by the WFOs to minimize travel time to the gage sites. If this method is formalized and a training package prepared, this method could be utilized to improve the gridded TRO estimates, thereby improving the FFG values the RFCs produce. Even though the future development of modeling tools may obviate the need for TRO, bankfull flows will still be required. Therefore, the site visits would not be wasted.

8. Defining an FFG Verification System

8.1. Issue

No verification system exists to provide feedback on the accuracy of the FFG RFCs provide to WFOs. Yet feedback from users and developers alike universally acknowledges the need for an FFG verification system. While a national verification program for RFC river forecasts exists, there is no corresponding program to address RFC FFG values. Verification is required to measure current performance and to establish a baseline to be used to quantify the effectiveness of future enhancements. Demonstrated improvements in FFG will lead to improved flash flood forecasting service.

8.2. Possible Solutions - Develop a national FFG Verification system

An independent team should be established to develop and implement a comprehensive national FFG verification program. This should include the design and implementation of a FFG database and statistical analysis software. The team also should determine if this capability could be incorporated into the national river verification program, or if an independent FFG verification program should be developed. Analysis capabilities should be developed to work on a scale compatible with existing products and services, and efforts should be coordinated with any development work to ensure compatibility with any introduced changes. Verification requirements must identify flash flood events which occur but are not predicted, as well as predicted events that don't occur.

Even though it is estimated a system could be developed within 2 years, the following issues will need to be addressed.

8.2.1. Overcome lack of available data to conduct verification analysis of FFG

Data on flash flooding events is not readily accessible. Two major concerns have been identified:

1. Lack of specific information in storm data reports, and
2. Lack of stream response data.

8.2.1.1. Storm Data

The information collected by WFOs in Local Storm Reports (LSR) products submitted to National Climatic Data Center (NCDC) often is done on the fly during the event due to staffing limitations. Once an event has been verified no further attempt is made to gather further data due to time constraints. This data is archived at the county level in Storm Data reports and is not correlated to RFC basins. Valuable spatial information collected in the LSR which could be used for subsequent RFC program evaluation is then lost. For example, WFO reports may contain information on specific locations within a county which experienced flooding. These details are not logged in the database. As our operational abilities continue to move further toward higher resolution gridded information, we need to capture all available details of individual events for future analysis. Further complications have been introduced with the introduction of small scale basins delineated in FFMP. These basins are defined at a much smaller scale than RFC basins, and there is no cross reference between the two data sets.

A solution to the problems listed above is to enhance Storm Data archives to include more detailed flash flooding reports including specific location information. This might be accomplished by adding capabilities to the FFMP program to allow forecasters to identify specific area details as part of the LSR process. This could be in the form of a delineation tool to allow a forecaster to draw a polygon around the area of reported flash flooding. Critical FFG verification information such as basin identifier and location could automatically be correlated to corresponding RFC basins.

Another potential solution would allow the vector coordinates of a forecaster delineated polygon to be recorded by the FFMP during the LSR data collection process. This information could be recorded as a gridded field for use in model evaluation.

This detailed event information could be used directly in verifying RFC FFG provided in small basin or gridded form. This would provide the highest level of detailed spatial information currently available and would be the most compatible format for future programs operating at higher spatial resolutions, e.g. distributed models. It would also be useful in identifying urban flooding events which are not controlled by natural channel systems.

One shortcoming is the subjective nature of reporting storm event information which does not necessarily provide adequate data to support RFC model verification of bankfull conditions.

It is estimated that the capabilities to capture finer detailed data could be developed in a few months.

8.2.1.2. Stream Response Data

The other concern related to lack of data for use in FFG verification is the ability to capture stream response to small scale flooding events. Efforts should be made to utilize all available information from existing USGS gage networks on all available small basins.

Strong consideration should be given to using data from the existing crest-stage gage network maintained by the USGS. Preliminary survey information found there is a network of USGS partial record gage sites (crest-stage recorders) which exists in many states (Appendix C), typically funded as part of a cooperative program to establish flood frequencies of small streams, often for use by state transportation departments. Ratings have been developed at these locations and bankfull stage may already be established. While data is collected periodically from these sites, only the annual peaks are available in the published record. Crest-stage recorders are very simple devices with minimal associated equipment costs.

The primary costs of the crest-stage gages would be associated with travel time required by USGS field technicians. Using event based information may allow more efficient travel planning, which would maximize benefits from field trips by USGS personnel. Exact costs would be dependent on USGS estimates. A cooperative program negotiated at the national level may provide for the increased USGS costs of data acquisition.

Also, there are networks of existing automated gage sites on small basins not currently modeled by RFCs. Automated gage sites exist on many small basins meeting flash flood criteria. These gages typically are not modeled by RFCs due to scale limitations. However, many of these sites report data at small time increments (less than one hour intervals). The high resolution spatial and temporal scale data provided by these gages could be utilized in verification of both FFG and distributed modeling.

8.2.2. Solving differences in varying precipitation data sources

Different precipitation data sources exist in the FFG system between the RFC and WFO, and within the RFC itself. Verification of FFG will require identifying any differences in precipitation estimates used at the WFO and the RFC.

Rainfall intensity is a major factor in predicting flash flooding. RFC models which derive FFG values may use either MPE radar rainfall estimates (MAPX) or gage derived fields (MAP) as input. The precipitation data source affects the ambient soil moisture values controlling FFG. Soil moisture states of rainfall/runoff models are the baseline for determining FFG values. Sensitivity analysis of the Sacramento Model (Burnash, et al 1973) has demonstrated the dominant source of model error in the rainfall-runoff relationship is attributed solely to precipitation input. Thus, basin precipitation values are the single most critical element in modeling soil moisture. These states are subsequently the controlling parameter in determining the FFG values used by the WFOs.

RFC forecasters manually control which precipitation data type to use for a given event during forecast operations. It currently is not possible to record which precipitation data type was used in the OFS database. This makes it very difficult to analyze quantitatively the forecast model rainfall-runoff states supporting FFG.

Once FFG is issued from the RFC, guidance values are compared to radar rainfall estimates from individual WFO WSR-88D products through the FFMP program. These radar estimates are derived from the Digital Hybrid-scan Reflectivity (DHR) products, while the RFC radar estimates are derived from Digital Precipitation Array (DPA) radar products. This difference in data source and scale may introduce error in the final product that is not due to FFG values themselves. Identifying differences in precipitation data is necessary to isolate FFG systematic error. This error may be due to the rainfall-runoff modeling component or the operational radar estimates at the WFO.

Possible solutions to these problems are:

8.2.2.1. Archive RFC Precipitation Input

The different potential sources of precipitation input used at an RFC, either MPE-based or gage-only derived, should be archived for FFG verification.

An OFS technique could be developed allowing RFCs to archive the "operational" time series used to maintain the rainfall-runoff model. This may be either radar estimates, gage estimates, or a combination of both. This data should be incorporated into the national river forecast verification database, or be cataloged in a separate national FFG verification database. This will provide a permanent record of the precipitation estimates used to balance the RFC forecast model.

This OFS enhancement request already has been made, but is a low priority item for development. There would be minor additional database storage requirements to capture this additional data.

8.2.2.2. Archive the WFO radar precipitation estimates used in FFMP in the FFG verification database

The radar precipitation estimates used in FFMP should be incorporated into the national river forecast verification database, or cataloged in a separate national FFG verification database. These estimates may be derived from either WFO MPE or DHR products. This will allow all possible precipitation estimates to be available for verification. It will require additional database storage requirements and take upwards to two years of development time.

8.2.3. There is no consistent definition of "flash flood" criteria represented by the FFG

The majority of flash flood reports received by WFOs are from various urban flooding situations or road inundations. The current FFG system was designed to represent bankfull conditions on small stream channels. It was not designed to represent flooding from urban runoff where there is no well defined natural drainage network. Yet this is where most flash flooding occurs, or is known to occur. Therefore, we currently are applying FFG incorrectly in most documented cases. Storm Data reports document flash flood event type under the category "urban/small stream". We need to differentiate the flash flood event type as urban inundation or over bank streamflow conditions in the Storm Data archives. This will ensure we can identify the FFG performance under the bankfull conditions it was designed to represent. Conversely, this will facilitate identifying areas of urban flash flood threats. This information will be useful in future development of FFG techniques to address urban flooding.

Efforts should be made to provide a clear definition of what flooding criteria FFG is designed to represent, as well as what conditions it does not represent. A flash flood classification is needed to differentiate urban from non-urban floods in the Storm Data records.

Potential approaches to addressing these issues are:

a. Develop a consistent national definition of flash flooding as represented by the FFG. As new capabilities are added for quantifying guidance values in urban and other non-soil-moisture driven threat areas, the definition should be updated to keep pace with the capabilities.

b. Ensure the national Storm Data archive is consistent with this definition and accurately is reflected in the LSR reporting process (NWS Instruction 10-517).

By identifying and documenting event details we will be able to provide a more thorough analysis of current and future guidance, with only minor additional time required to enter data in the WFO LSR products.

9. FFG Misconceptions

9.1. Issues

Feedback from RFCs and WFOs before this team was formed and during the course of this team's existence point out that both RFC and WFO personnel need additional training on FFG, its application, and its shortcomings. Misconceptions existing at the WFOs on the use of FFG include:

- perceiving FFG as "gospel" versus guidance,
- issuing warnings only when rainfall exceeds FFG and not beforehand,
- believing FFG is designed for forecasting urban flooding, even though it is produced to help with small stream flooding.

Similar misunderstandings exist with RFC personnel, limiting the support service provided to their HSAs.

9.2. Solutions

The scientific basis and operational use of the FFG product need to be clearly defined and understood. Additional training in flash flood modeling and FFG is needed both for WFO and RFC personnel. Specific issues to be addressed include:

- What is the effective spatial and temporal resolution of FFG?
- What is the scientific foundation on which the operational methodology to produce FFG is based?
- What are the strengths and limitations of FFG?
- How should FFG be used to address flooding in urban areas?
- How is the accuracy of FFG being addressed?
- How are the science and implementation changing?

10. Need for a well defined national support structure for FFG production and use

10.1. Issues

It is clear from the team's investigation that overall coordination and support of FFG needs improvement. To better define a national support structure, the following critical areas have been identified:

- Incorporation of new science and technology into FFG
- Coordination between RFCs in FFG product generation
- Coordination between WFOs and RFCs in intended use of FFG
- Provision of national training on FFG production and use
- Provision and/or coordination of national technical support
- Need for a well defined flash flood program, a part of which is the generation and application of FFG

10.2. Solution: Improve national support structure for FFG

As FFG is critical to support hydrologic watch/warning decision assistance tools in AWIPS at field offices, a refined science and software development support structure is needed at NWSH, working in cooperation with the regions. OCWWS HSD should lead this definition effort.

Many issues need to be addressed by this support structure, but some of the key elements include:

- Ensuring that the scientific basis and operational use of the FFG is clearly defined. And, as the underlying science and implementation of FFG evolves, OCWWS HSD must continue to provide updated information to the field.
- Continuous oversight and coordination of the various components required to provide and support flash flood services by the NWS, both in their operational use and in their evolution.
- NWSH and the regions should lead coordination efforts to reconcile differences in the FFG product of neighboring River Forecast Centers (RFCs). This is particularly important given 30% of Weather Forecast Offices (WFOs) are supported by multiple RFCs.
- An effective FFG training package needs to be developed and provided to forecasters nationwide (see Section 9).

11. Recommendations

The team's investigations led to proposing "patches" to the current system for generating FFG, starting development on two approaches much different than the existing system, and to developing an FFG verification system. Currently, there are no known resource conflicts among the recommendations. Therefore the team recommends the following actions be taken towards improving the state of the FFG generation process for the next one to two years:

1. No one approach provides for the needs of the entire country in producing FFG values, especially for the time horizon of the team's focus. However, in the one to two year time frame, the team believes significant progress can be made in the following areas and recommends undertaking efforts to address each of the listed items:

    a. Optimize the performance of the existing FFGS system:
        i. Eliminate gaps within each RFC's borders and along neighboring RFC boundaries as well as eliminate grid cell overlap between RFCs,
        ii. Modify existing OFS code to ensure proper grid cell assignment,
        iii. Develop necessary FFG value consistency across adjacent RFC boundaries,
        iv. Develop capability to edit graphically FFG and ThreshR grids.
        v. Formalize the site visit method for TRO derivation and start additional visits at more locations.

    b. Develop the methodologies to provide FFP information for areas of the country where rainfall intensity and land characteristics influence the incidence of flash flooding more than soil moisture,

    c. Start the development of a new approach, Statistical Distributed modeling, that can be substituted for the current system when SD is deployed and will provide development work beneficial for the evolution towards distributed hydrologic modeling. This approach and that listed in item b. above initially will focus on their particular problem areas but additional development work must be coordinated to minimize conflicts and redundancy.

    d. Design and develop an FFG verification system, making sure that it will support the verification needs of the existing approach as well as the two revised approaches recommended.

2. One common thread in all of the proposed individual solutions is the need for coordination and oversight at the national and regional level for the RFCs' responsibilities in support of the national flash flood watch/warning program. Whether working to "patch" the existing system, coordinating the enhancement and development work done for the RFCs and for the WFOs, or developing and providing training and education materials for both the RFCs and the WFOs, it is apparent that a strong national presence is needed to ensure the needs of the NWS flash flood program are met.

Therefore, the team recommends OCWWS HSD take the lead in identifying the needs for national oversight and coordination of these recommendations and work with other national and regional offices in establishing roles and responsibilities.

Based on this team's investigations, critical areas to be addressed in the very near future are:

a. Provide clarification on the purpose, application, generation and applicability of FFG as it currently exists and is implemented and to provide definition updates as new capabilities are developed and deployed,
b. Develop or oversee the development of training materials to educate RFC and WFO staff members on all aspects of the generation and application of FFG, and to ensure that this information is kept current,
c. Work to ensure optimum technical support to the RFCs on the FFGS,
d. Provide the internal NWS coordination needed to optimize current FFGs implementation as this effort crosses office and regional boundaries,
e. Provide the internal NWS coordination necessary to ensure development and enhancement efforts for the provision of flash flood information are resource-effective. These efforts should be communicated and coordinated with those that utilize such information.

12. Figures

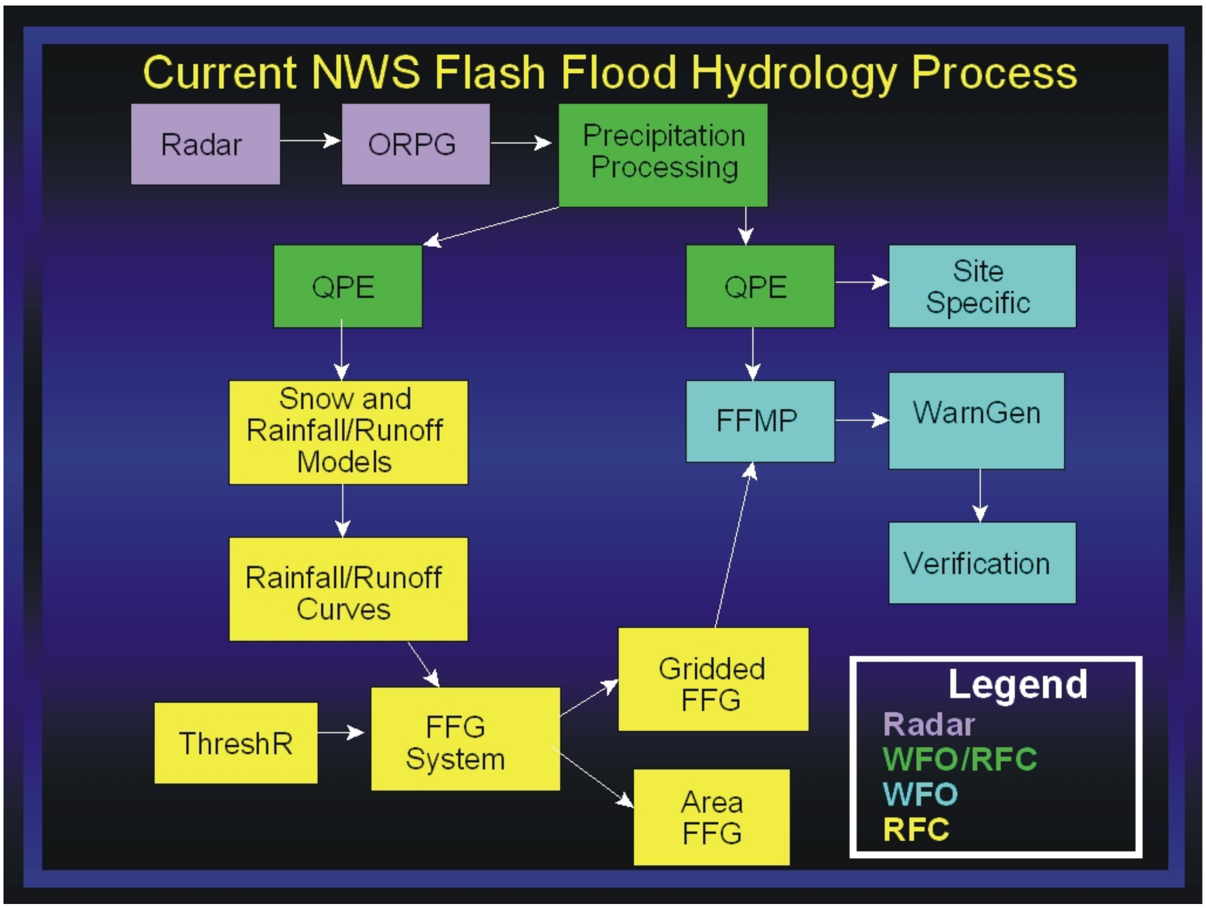

Figure 2
Current NWS Flash Flood Hydrology Process

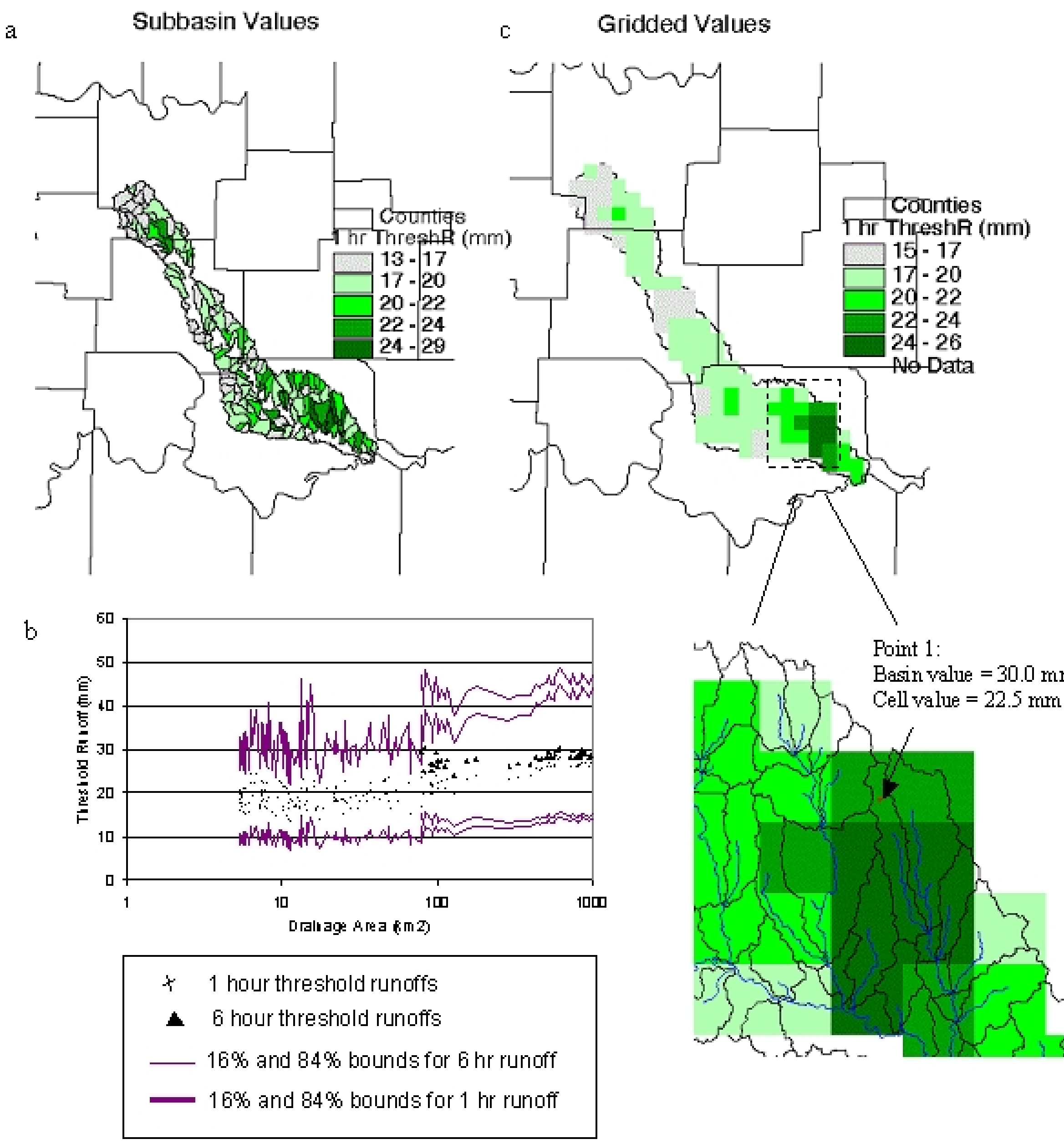

Figure 3 a. 1-hr Threshold Runoff Estimates for the Blue River Basin – computations for small basins. **b.** 1-hr and 6 hr threshold runoff vs. drainage area w/ uncertainty bounds **c.** (top) Small basin values interpolated to HRAP (16 km^2) grid cells. (Bottom) At a given point, the representative value for a small subbasin differs from an interpolated grid cell value. Single grid cells often overlap multiple subbasins

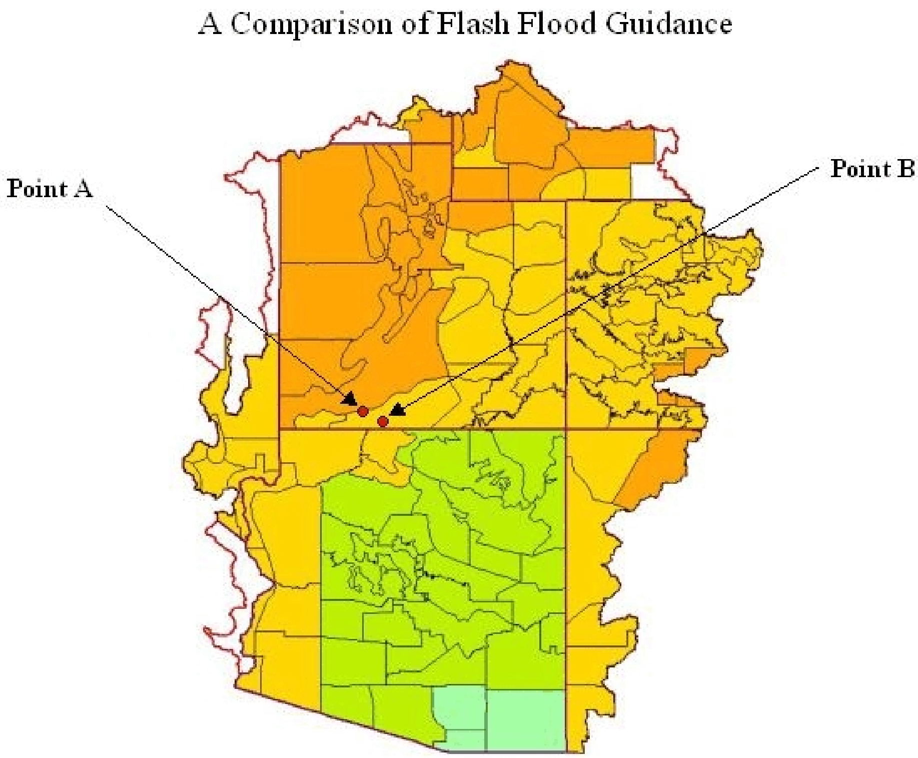

Figure 3 - Sample locations of varying drainage characteristics

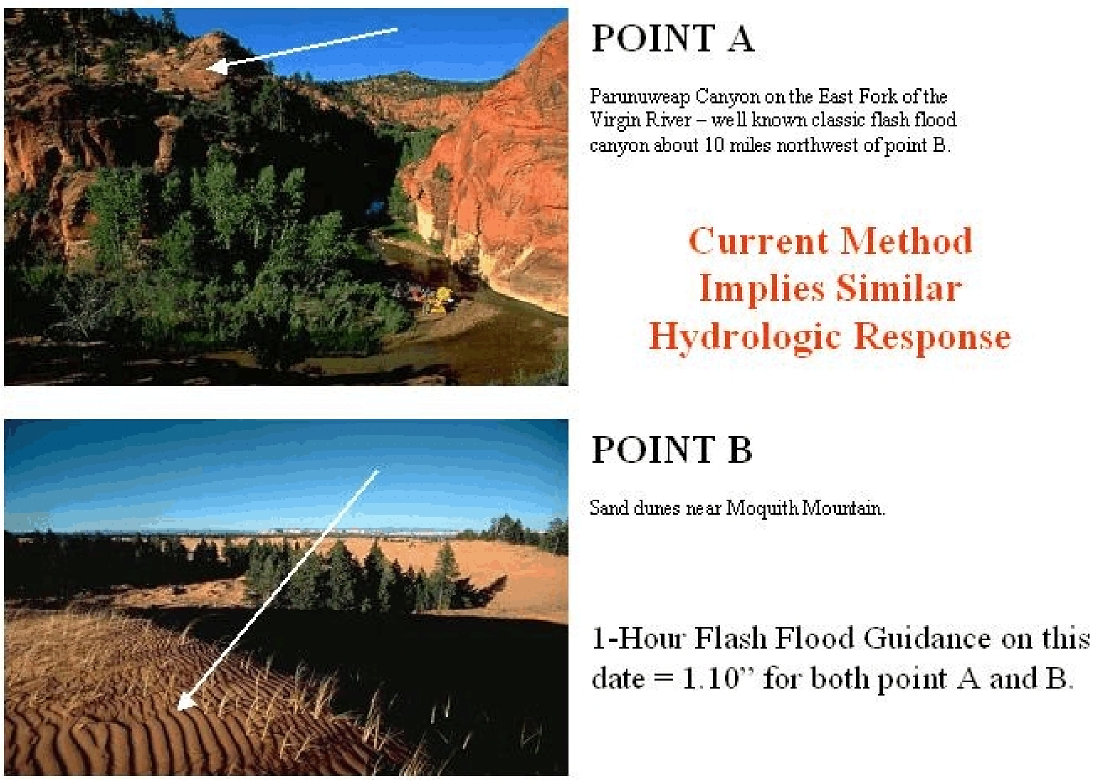

Figure 5 - Varied watershed characteristics

1 Hour Flash Flood
Guidance = 1.10”

FFG for 8/15/2001

Figure 6 - Bankfull conditions?

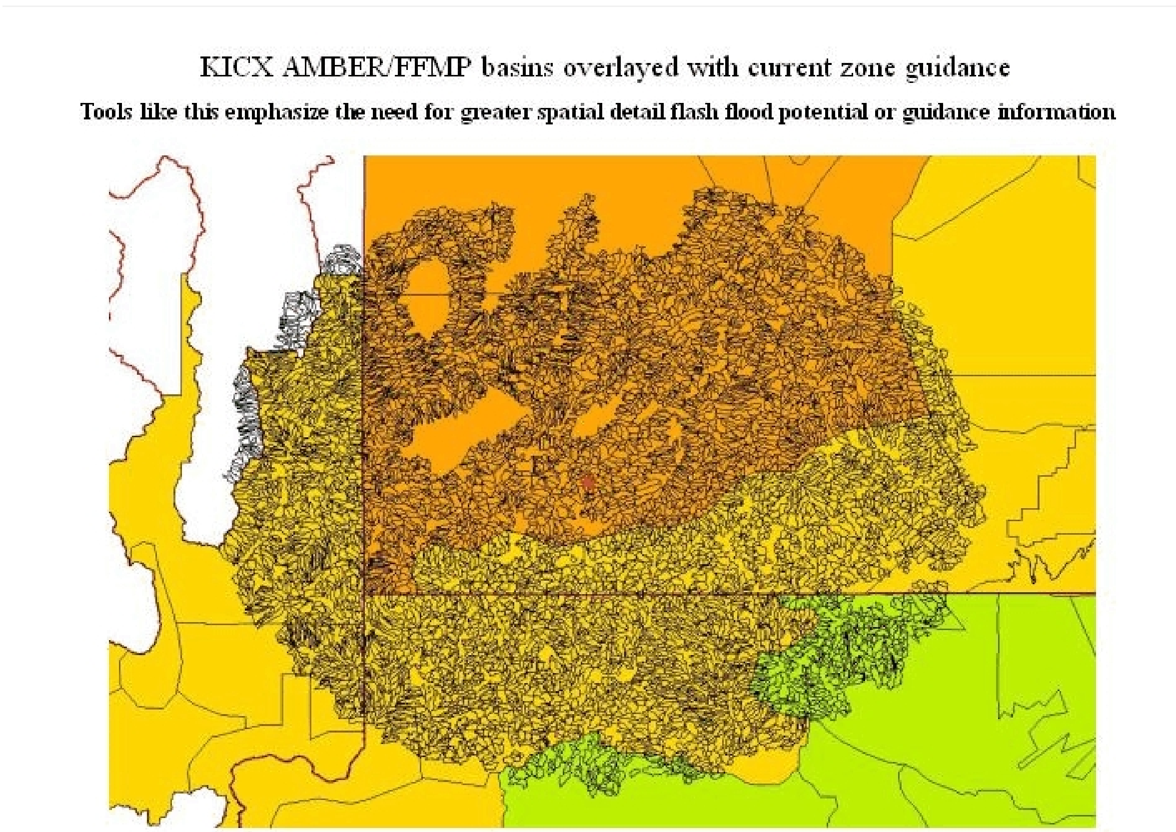

Figure 7 - Sample FFMP basin delineation - Cedar City, UT

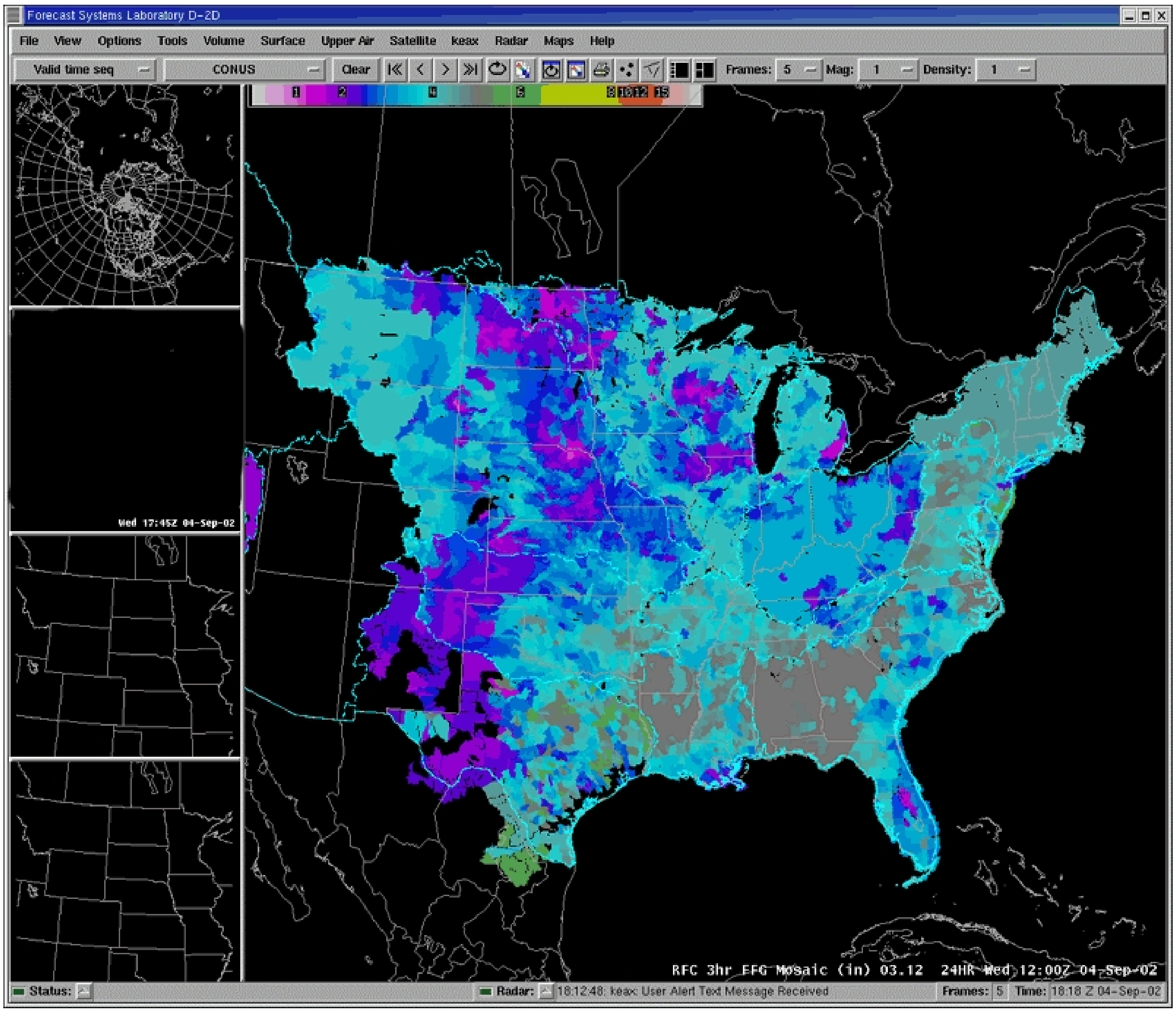

Figure 8 - RFC 3 Hour FFG

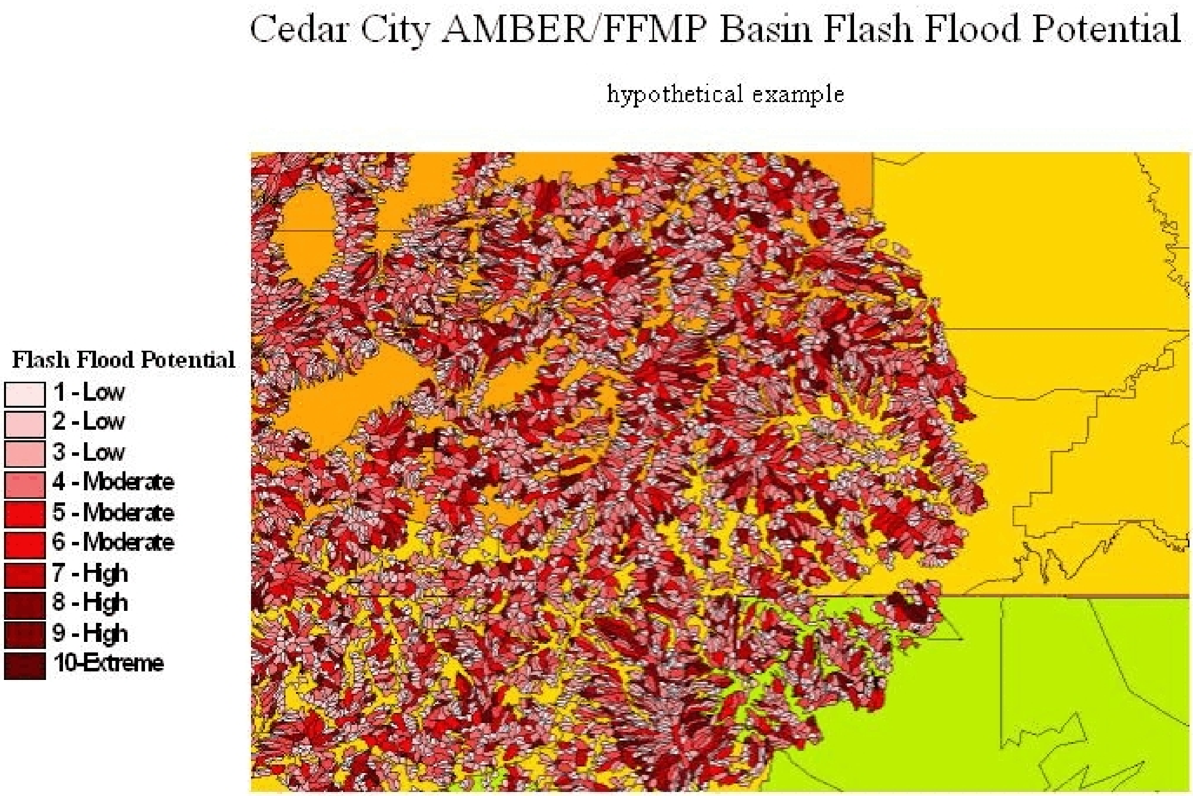

Figure 9 - Sample Flash Flood Potential Map

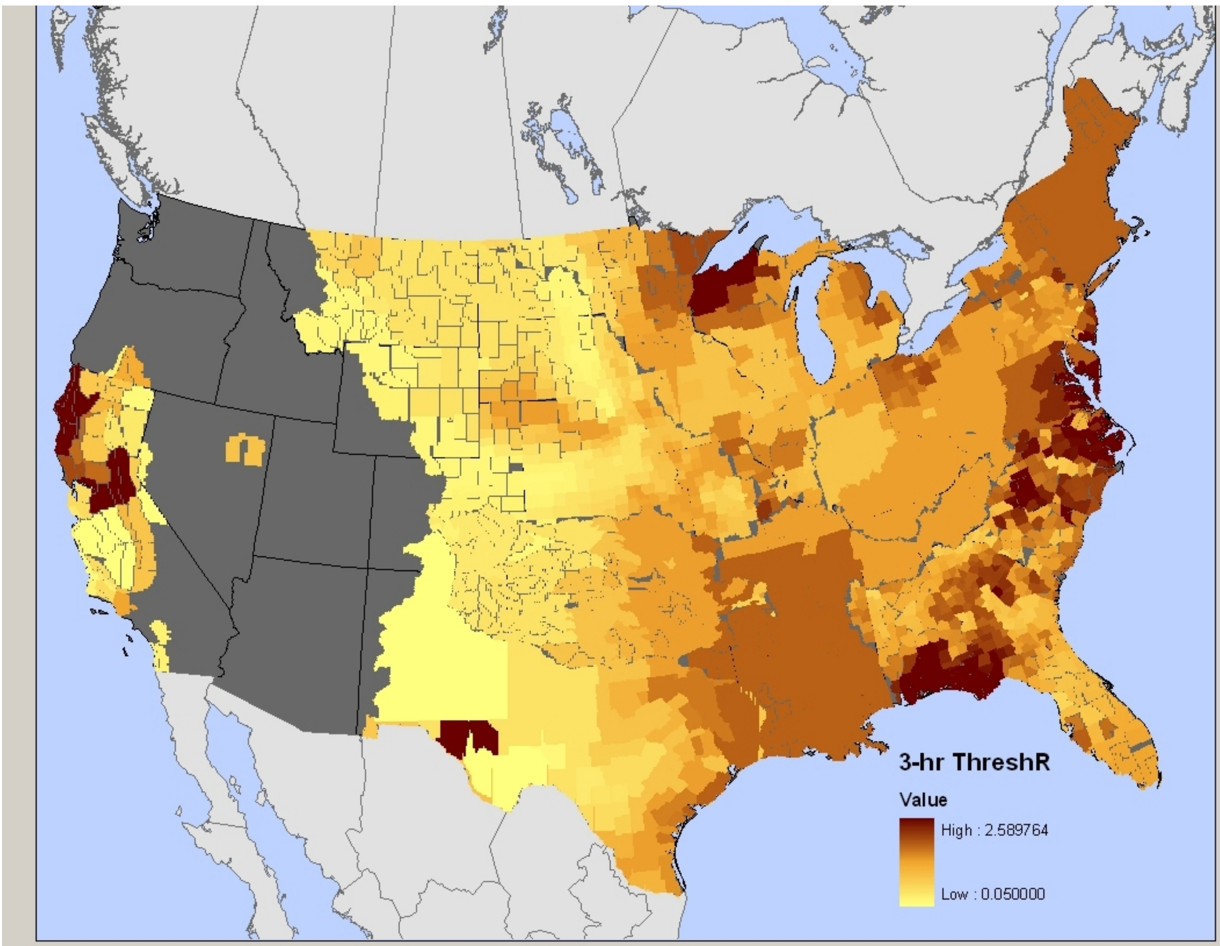

Figure 10 - RFC 3 Hour Threshold Runoff Mosaic

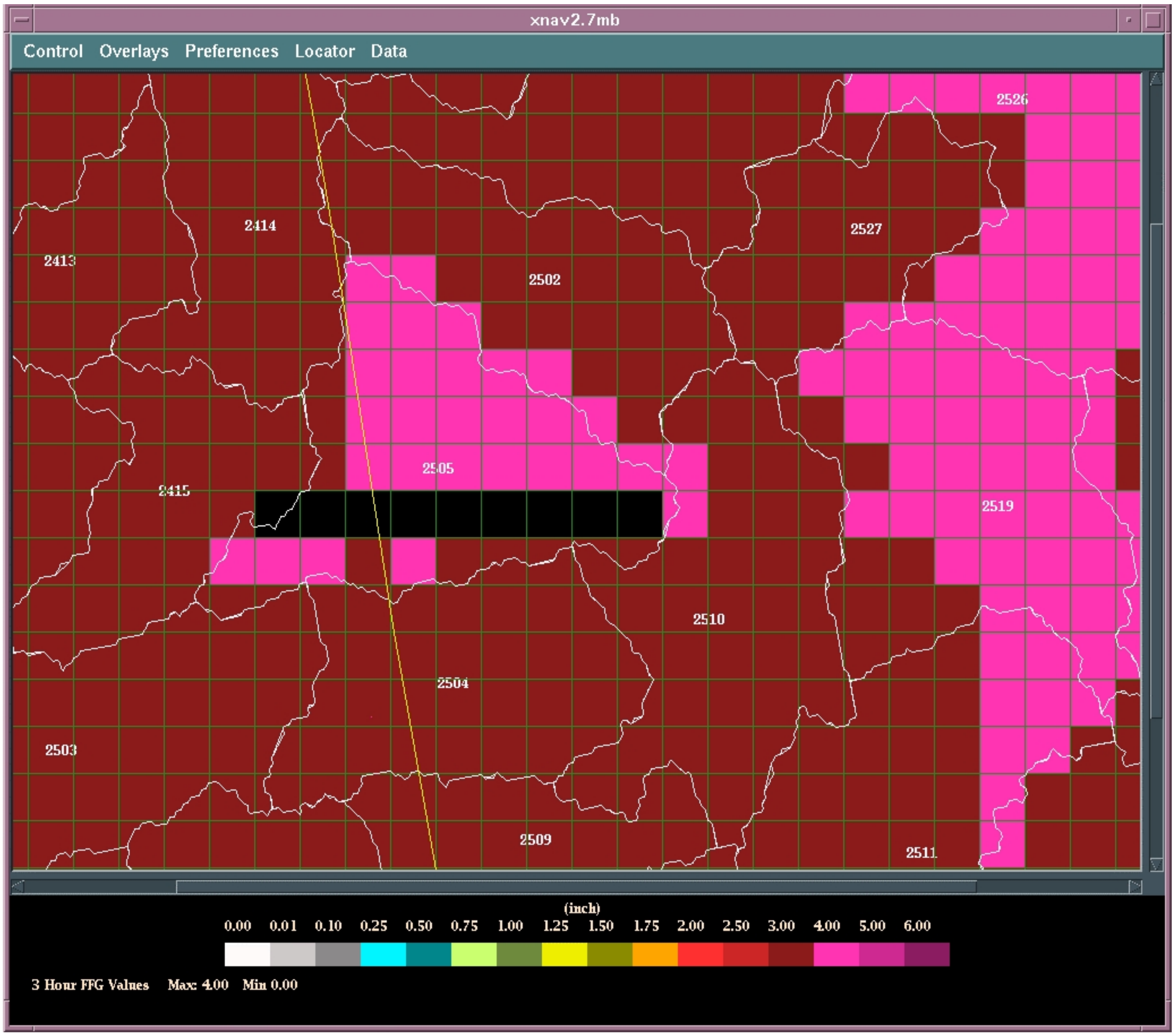

Figure 11 - Unassigned grid cells

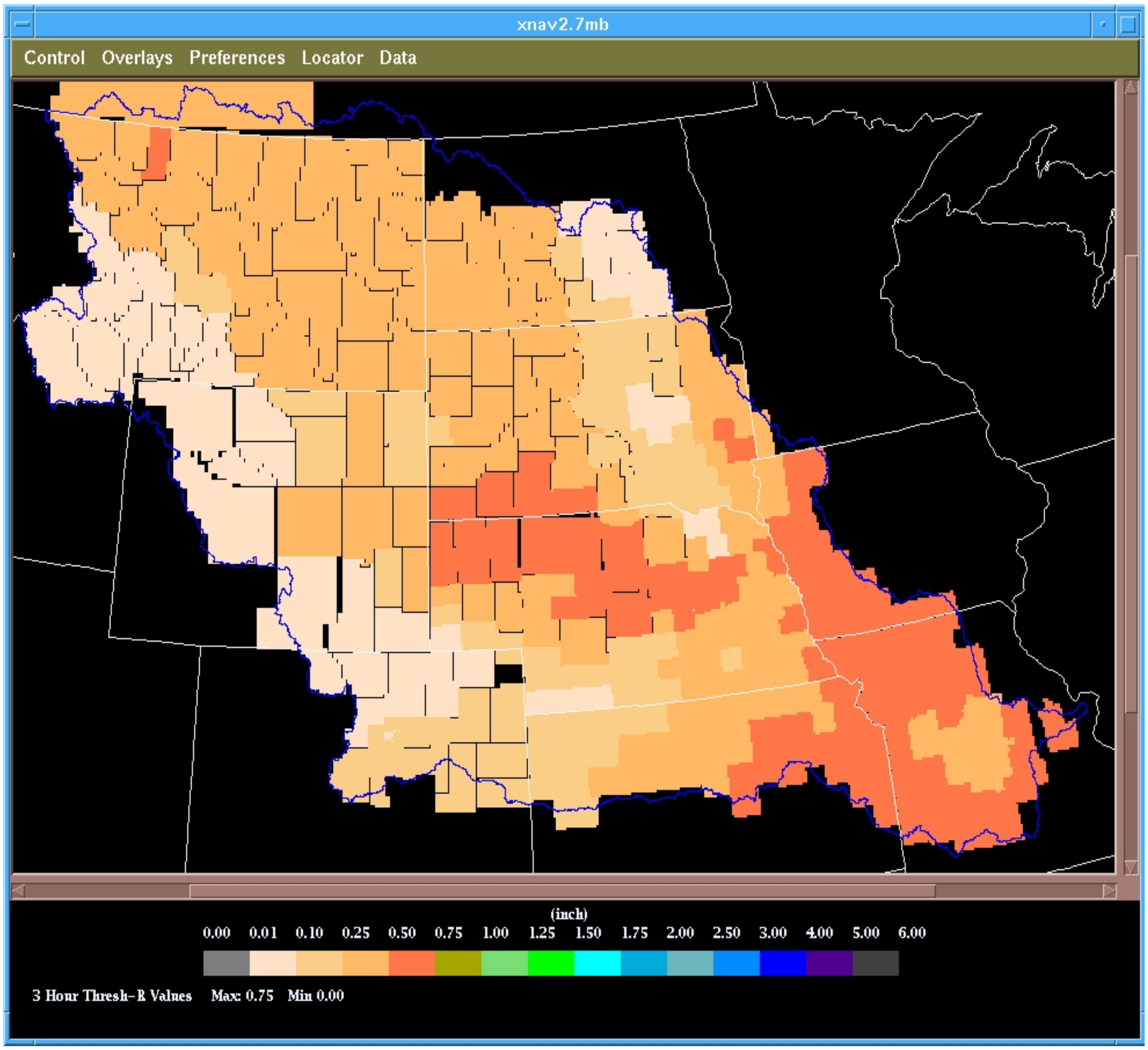

Figure 12 - Gaps in Threshold Runoff Values

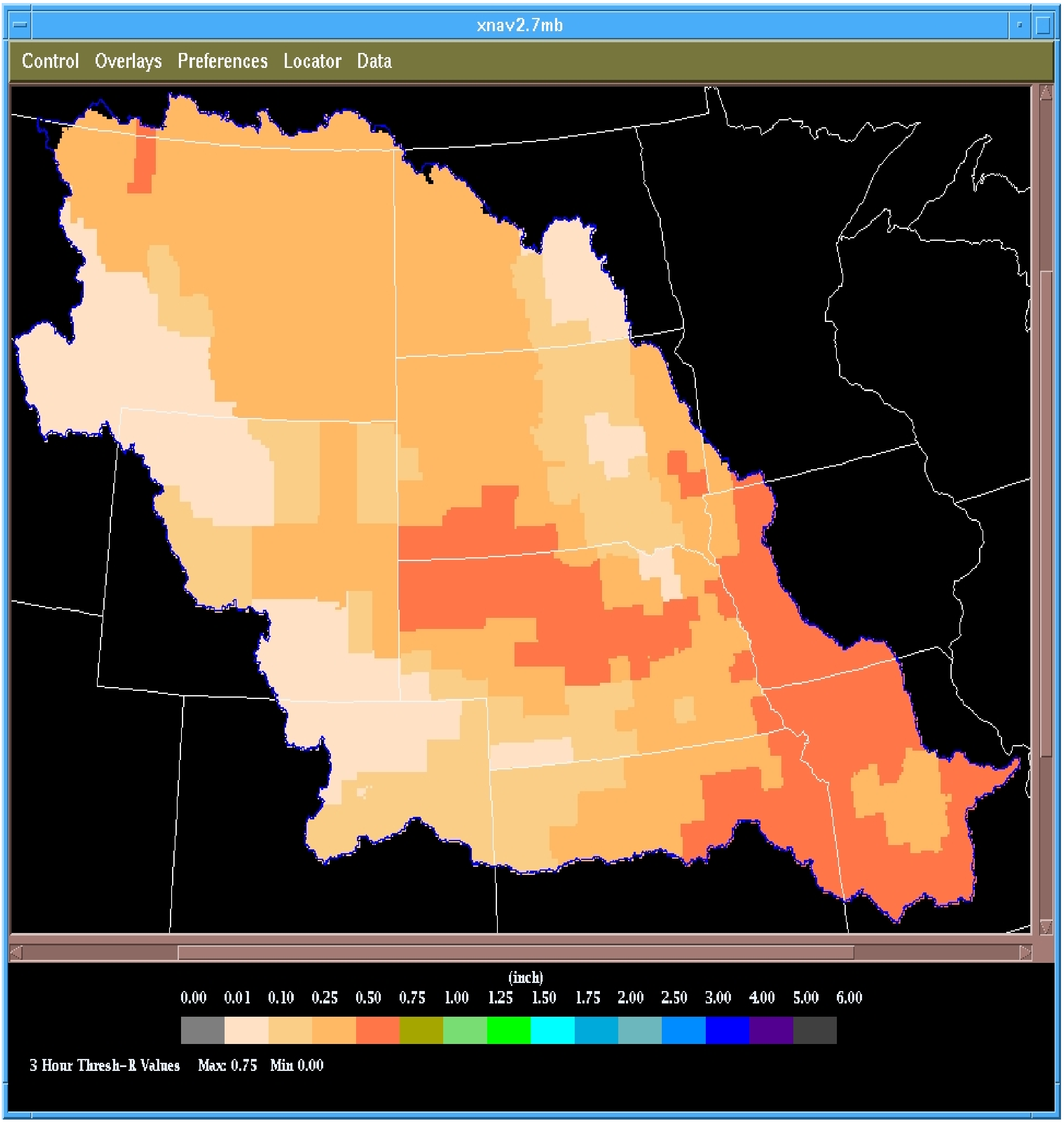

Figure 13- Threshold Runoff Values after Editing

13. Appendices

Appendix A

Flash Flood Guidance Improvement Team Charter

Vision: Improved services for small basins with fast hydrologic response.

Mission: Develop a plan to modify or develop procedures to produce hydrologically sound, national flash flood guidance at RFCs for use operationally at WFOs in the watch/warning decision making process. The plan will contain realistic recommendations to improve flash flood guidance in the short term (1-2 years).

Scope of Authority/Limitations:

- Recommendations must be efficient and cost effective
- Travel expenses will be covered by each team member's Region/Office
- Team will consult with representatives from all phases of the flash flood program.
- Team will consider flash flood program issues raised in the RFC Operations Team draft report.
- Team will ensure recommendations are in compliance with Section 508 - Rehabilitation Act and the Architectural and Transportation Barriers Compliance Board Electronic and Information Technology Accessibility Standards

Termination Date: The team will be formed and commence activities in July 2002 and remain assembled no longer than 6 months.

Success Criteria/Deliverables:
Provide draft consensus recommendations to the NWS Corporate Board Standing Committee on Operations by December 13, 2002.

Team Membership: The team will be made up of at least three Regional representatives, one from the Office of Hydrologic Development and one from the Office of Climate, Water, and Weather Services' Hydrologic Services Division. Team leader will be chosen by the team.

Team members are:
AR: Ben Balk (APRFC)
CR: Mike DeWeese (NCRFC)
CR: Gene Derner (MBRFC)
ER: Joe Ostrowski (MARFC) - Team Leader
WR: Brian McInerney (SLC WFO) OCWWS-HSD:
OHD:
SR: Greg Story (WGRFC) also represents NWSEO
WR: Brian McInerney
OCWWS-HSD: Michael Mercer
OHD: Seann Reed

Appendix B: Current RFC FFG Production Status

	What formats do you generate?	Use modernized thresh-R approach?	Which temporal (hour) products do you issue?	What is the frequency of issuance?	Are products quality controlled?
NERFC	Zone	No, but will in future	1, 3, 6, 12, & 24	12 Z	Yes, Manually with a GIS comparison
OHRFC	Gridded & County	No, but will in future	1, 3, 6, 12, & 24	00Z & 12Z	Yes, Manually
MARFC	Gridded to county	No, but working on it	1, 3, 6, 12, & 24	00Z & 12Z	Yes, Manually
SERFC	Gridded & Zone	No	1, 3, 6, 12, & 24 E 1, 3, 6 in S Portion	00Z & 12Z	No
WGRFC	Gridded county/ zone hybrid. Zone in NM/W TX	No	1, 3, & 6	0230, 1130, 1430, 2030 local time	No
ABRFC	Gridded & County	No	1, 3, & 6	00Z, 12Z, 18Z (also 6Z when in 24 hour mode)	No, (QC'd approx. twice per week)
LMRFC	Gridded & Zone/text	No	1, 3, & 6 (12 & 24 for some zones)	00Z & 12Z	Yes
NCRFC	Gridded & County	No, under evaluation	1, 3, 6	00 Z & 12Z	Yes
MBRFC	Gridded & County	No	1, 3, 6	00Z & 12Z	Yes
NWRFC	Does Not Produce	N/A	N/A	N/A	N/A
CNRFC	Zone/text (testing gridded)	Yes, Modified	6 (1 & 3 being tested)	18Z	No
CBRFC	Zone/text (working on gridded)	No	1, 3, 6	12Z	Yes
APRFC	Does Not Produce	N/A	N/A	N/A	N/A

Appendix C. Preliminary Partial Survey of USGS Crest-Stage Recorders

State	Number of Crest-Stage Recorders
Colorado	21
Illinois	303
Iowa	59
Kansas	27
Louisiana	38
Michigan	76
Minnesota	88
Mississippi	80
Missouri	39
New Mexico	26
North Dakota	34
Texas	50
Wisconsin	85
Wyoming	27

14. References

Carpenter, T.M., J.A. Sperfslage, K.P. Georgakakos, T. Sweeney, and D.L. Fread, 1999, National threshold runoff estimation utilizing GIS in support of operational flash flood warning systems, Journal of Hydrology, 224, 1-2, pp. 21-44.

Finnerty, B.D., Smith, M.B., Seo, D.J., Koren, V., Moglen, G.E., 1997, Space-time scale sensitivity of the Sacramento model to radar-gage precipitation inputs, Journal of Hydrology, 203, 21-38.

Hershfield, D.M., 1961, Rainfall Frequency Atlas of the United States for Durations from 30 minutes to 24 hours and Return Periods from 1 to 100 Years, Technical Paper No. 40, U.S. Weather Bureau.

Koren, V.I., Finnerty, B.D., Schaake, J.C., Smith, M.B., Seo, D.J., Duan, Q.Y, 1999, Scale dependencies of hydrologic models to spatial variability of precipitation, Journal of Hydrology, 217, 285-302.

Koren, V.I., Smith, M., Wang, D., Zhang, Z., 2000, Use of Soil Property Data in the Derivation of Conceptual Rainfall-Runoff Model Parameters, 15th Conference on Hydrology, American Meteorology Society, Long Beach, California, 103-106.

Koren, V., Smith, M., Duan, Q., 2001, Use of a priori parameter estimates in the derivation of spatially consistent parameter sets of rainfall-runoff models, to appear in Advances in the Calibration of Watershed Models, AGU Water Science and Applications Series, Qingyun Duan, Soroosh Sorooshian, Hoshin Gupta, Alain Rousseau, and Richard Turcotte, Editors.

Reed, S., D. Johnson, T. Sweeney, 2002, Application and National Geographic Information System Database to Support Two-Year Flood and Threshold Runoff Estimates, Journal of Hydrologic Engineering, May/June.

Reed, S., V. Koren, Z. Zhang, M. Smith, D.J. Seo, 2002, Distributed Modeling for Improved NWS River Forecasts, Proceedings of the Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, July 28-August 1.

Rodriguez-Iturbe, I, M. Gonzalez-Sanabria, R.L Bras, 1982a, A Geomorphoclimatic Theory of the Instantaneous Unit Hydrograph, Water Resources Research, 18, 4, 877-886, August.

Rodriguez-Iturbe, I, M. Gonzalez-Sanabria, G. Caamano, 1982b, On the Climatic Dependence of the IUH: A Rainfall-Runoff Analysis of the Nash Model and Geomorphoclimatic Theory, Water Resources Research, 18, 4, 877-886, August.

Sweeney, T.L., Oct. 1992, Modernized Areal Flash Flood Guidance, NOAA Technical Memorandum NWS Hydro 44, Silver Spring, MD.